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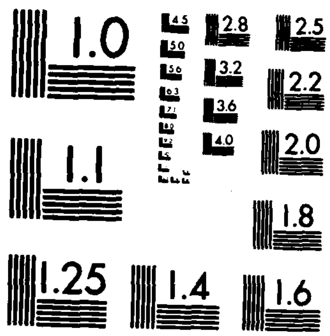

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RESEARCH STATUS AND RECOMMENDATIONS FROM THE ALASKA WORKSHOP ON GRAVITY WAVES AND TURBULENCE IN THE MIDDLE ATMOSPHERE

AD-A140 939

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This report summarizes the efforts of a working group which met to discuss gravity wave and turbulence processes in the middle atmosphere. The objectives were to review the current theoretical understanding and observational capabilities in this field and to suggest additional studies that would further our knowledge of these processes and their effects on the large-scale circulation of the middle atmosphere. The results of that review and recommendations for the design of future programs for studies of middle atmosphere dynamics are presented. Our current theoretical understanding of gravity wave and turbulence processes in the middle atmosphere is fairly

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20. removes and concentrates oxygenates from a sample stream that also contains other organic compounds such as hydrocarbons and chlorinated hydrocarbons. A separation of a complex mixture of metal chelates has been accomplished using a bonded-phase, wall-coated fused silica capillary chromatographic column. Limited success has resulted from attempts to separate optical isomers when a chiral metal chelate is incorporated into a chromatographic stationary phase.

ABSTRACT

Recently, a small group of atmospheric scientists met to discuss gravity wave and turbulence processes in the middle atmosphere. Our objectives were both to review the current theoretical understanding and observational capabilities in this field and to suggest additional studies that would further our knowledge of these processes and their effects on the large-scale circulation of the middle atmosphere. It is hoped that our review and recommendations will be useful in the design of future programs for studies of middle atmosphere dynamics.

While our current theoretical understanding of gravity wave and turbulence processes in the middle atmosphere is fairly primitive, it is likely that theoretical and modeling studies will contribute important quantitative information on gravity wave excitation, propagation, and dissipation mechanisms and effects over the next few years. Likewise, our knowledge of gravity wave and turbulence morphology, parameters, and processes will likely expand substantially following the installation, and particularly the combination, of various observing systems.

1. INTRODUCTION

The influence of small-scale motions on the large-scale circulation is one of the most challenging aspects of the study of the general circulation of the atmosphere. It is well known that small-scale moist convection is an essential feature of the tropospheric general circulation, but it is less appreciated that gravity waves and turbulence are essential contributors to the general circulation of the middle atmosphere. It is possible to produce a qualitatively correct simulation of the tropospheric circulation (at least outside the tropics) without including moist convection. But in the mesosphere, the meridional temperature distribution and the mean meridional wind cannot even qualitatively be simulated without incorporating the drag that gravity waves exert on the mean flow. In the stratosphere, the role of gravity waves is less obvious, but there are indications that gravity wave drag may be important in the winter polar stratosphere.

Some of the evidence supporting the role of gravity waves in the middle atmosphere described above is reviewed in the remainder of this section. Then in Section 2, we briefly describe two types of models that have been used in previous studies of the middle atmosphere. A discussion of the characteristics and the likely middle atmosphere effects of gravity waves is provided in Section 3. Section 4 describes a variety of observational systems that have been employed for gravity wave and turbulence studies. Also presented are a discussion of their relative advantages and disadvantages, a description of their present and likely future capabilities, and a review of some of the observational results obtained to date. Finally, Section 5 provides a discussion of the modeling, theoretical, and observational (both measurement and equipment) needs identified by the workshop participants.

A crude model of the middle atmosphere structure can be obtained by calculating the zonally symmetric middle atmosphere temperature structure that corresponds to radiative equilibrium (see Figure 1) and the resulting mean zonal geostrophic wind (see Figure 2) following Geller (1983). Compared with observations, this radiative equilibrium state predicts too warm (cold) a summer (winter) stratopause and too warm (cold) a summer (winter) mesopause. Also, magnitudes of both the summer and winter mesospheric jets are too large, and the vertical shear of the mean zonal wind fails to reverse in the upper mesosphere. Meridional and vertical motions are absent in this radiative and geostrophic equilibrium solution.

Figure 3 shows the results of the same calculation but with an appropriately chosen Rayleigh drag incorporated to approximate the effects of gravity wave dissipation (Geller, 1983). In this case the summer stratopause is cooler and the winter stratopause is warmer than in the radiative equilibrium solution. In the mesosphere the meridional temperature gradient is actually reversed so that the winter mesopause is warmer than the summer mesopause. These features are in line with existing observations. Furthermore, the mean zonal jet structure closes with altitude in both hemispheres and has wind speeds more consistent with observations. Recent models also yield a summer to winter meridional flow, with upward motion (with accompanying expansion cooling) in the summer hemisphere, and downward motion (with accompanying compression heating) in the winter hemisphere. Such results indicate that the middle atmosphere temperature, zonal wind, and constituent structure (through the induced meridional and vertical motions) strongly depend on zonal momentum drag processes. This momentum is presumably transported upward from sources in the troposphere.

Outside the tropics gravity waves appear to be essential for understanding the annual cycle of the large-scale circulation. In the equatorial middle atmosphere the semiannual and quasi-biennial oscillations are of much stronger amplitude than the annual cycle. For the quasi-biennial oscillation and the stratospheric semiannual oscillation, it is believed that large-scale equatorial waves are the primary drivers. However, there is also a strong semiannual oscillation near the mesopause (peak amplitude at 80 km) which is likely to be driven by gravity waves and tides. However, to date no suitable mesospheric observations of gravity waves and turbulence in the equatorial zone have been made.

Gravity waves are thought to be mainly responsible for the vertical transport of momentum. The reasoning behind this is that the drag processes are required in both winter and summer, and gravity waves are present in both seasons. The other leading candidate, planetary waves, is known to be very weak in the summer.

The action of gravity waves is schematically indicated in Figure 4. In the absence of dissipation or reflection, a gravity wave grows exponentially with height (as indicated below the height of wave breaking) so that, eventually, the conditions for shear or convective instability result. At this point, the wave is assumed to lose energy through the production of turbulence so that the amplitude remains constant in the absence of varying $\bar{u}$. This causes a departure from exponential growth and a divergence of the vertical flux of horizontal momentum, causing an acceleration of the flow towards the phase speed of the wave. For a gravity wave spectrum of tropospheric origin, the result is a deceleration of the large-scale flow.

2. MIDDLE ATMOSPHERE MODELS

We may distinguish between two types of middle atmosphere models -- the mechanistic models and the general circulation models. General circulation models (GCMs) attempt to simulate all aspects of the large-scale circulation, while mechanistic models are designed to focus on only a limited range of dynamical processes. For middle atmosphere studies, mechanistic models typically do not seek to faithfully reproduce the details of the tropospheric circulation but rather specify the tropospheric forcing near the bottom of the middle atmosphere. Examples of this type of model are the works of Matsuno (1971), Schoeberl and Strobel (1978), and Holton and Wehrbein (1980). The middle atmosphere general circulation model, on the other hand, seeks to explicitly model the entire troposphere-middle atmosphere system. An example of this type of model is Fels et al. (1980).

a. Mechanistic Models of the Middle Atmosphere

Although all mechanistic models are simple when compared to GCMs, there is a wide spectrum of mechanistic models ranging from one-dimensional wave-mean flow interaction models to three-dimensional primitive equation models.

The minimum model which appears to be required to consider the effects of internal gravity waves on the general circulation of the middle atmosphere is a zonally symmetric, quasi-geostrophic beta-plane channel model. In such a model the mean wind and temperature are coupled through the thermal wind equation, and compensation for gravity wave driving in the momentum and thermodynamic energy equations occurs in the form of an induced mean meridional circulation. Such models have been used by Matsuno (1982) with a wave-damping parameterization, and Holton (1982) with Lindzen's (1981) wave-breaking parameterization. In these models, only a single meridional mode was allowed so that the meridional scale (and hence the Rossby depth) was imposed. However, despite their simplicity such models appear to be very useful for studying the response of the mean mid-latitude circulation to parameterized gravity wave driving.

Attempts to simulate the full latitudinally varying, zonally symmetric solstice circulation have been made by Miyahara (1983) and Holton (1983). Miyahara's model utilized the viscous wave-damping parameterization of Matsuno (1982), but with a more restricted wave spectrum. Holton adopted Lindzen's (1981) wave breaking parameterization. Both models were successful in simulating the gross features of the zonal mean circulation in both the summer and winter hemispheres although important differences between models and observations remain. Holton's model also incorporated a single zonal harmonic forced planetary wave in the winter hemisphere in some experiments, and he found dramatic effects due to the modulation of gravity wave transmission by planetary wave-mean flow interactions. Holton, however, did not consider any zonal dependence of wave breaking which should occur in the presence of nonzonal gravity wave sources and large-amplitude planetary waves; nor did he consider the refraction of gravity wave ray paths in the presence of longitudinally and latitudinally varying mean flows. The possible importance of these effects has been emphasized by Schoeberl and Strobel (1983) and Lindzen (1983).

b. General Circulation Models of the Middle Atmosphere

General circulation models of the middle atmosphere have not included parameterizations of gravity wave and turbulence effects to date. One reason for this is that, in most cases, the wave drag formulations that have been used in mechanistic middle atmosphere models have been tuned to give reasonable looking circulations. While such tuning is easily done in simple models, it is very time-consuming and expensive in general circulation models. Middle atmosphere general circulation models that extend to the mesosphere sometimes use fixed diffusion profiles of the type that appear in one-dimensional photochemistry models, but with smaller magnitudes (see Cunnold et al., 1980, Figure 5, and Hunt, 1981, Figure 1). Fels et al. (1980) use a Richardson number dependent parameterization for the vertical mixing of heat and momentum that is dependent on vertical grid resolution.

3. THEORETICAL DISCUSSION

Internal gravity waves are disturbances whose intrinsic frequencies $k(c-\bar{u})$ are smaller than the Brunt-Vaisala frequency. Their importance arises because:

i) They are the major components of the total flow and temperature variability fields of the mesosphere (i.e. shears and lapse rates) and hence constitute the likely sources of turbulence, and

ii) They are associated with fluxes of momentum that communicate stresses over large distances. For example, gravity waves exert a drag on the flow in the upper mesosphere. However, in order that gravity waves exert a net drag on the atmosphere, they must be attenuated.

There are two general types of processes that seek to attenuate gravity waves -- dissipation and saturation. Dissipation is any process that is effective independent of the wave amplitude while saturation occurs when certain wave amplitude conditions are met. Radiative damping is an example of dissipation while convective overturning, which arises when the wave breaking condition $|\frac{\partial T}{\partial z}| \sim \Gamma$ (or $u' \sim |c-\bar{u}|$) is met, is an example of saturation. The two processes are not mutually exclusive.

Saturation implies that the wave field has reached amplitudes such that either secondary instabilities (Lindzen, 1981; Dunkerton, 1982a) or nonlinear interactions, such as the parametric subharmonic instability (Lindzen and Forbes, 1983), can occur which limit further wave growth. In the atmosphere, amplitudes sufficient for saturation may result either from exponential growth with height or from the approach of a wave packet to a critical level. The saturation mechanism considered most common is the generation of convective or Kelvin-Helmholtz (KH) shear instabilities. Both instabilities were observed in the laboratory study of gravity wave propagation by Koop and McGee (1983), but convective instabilities were found to dominate when both were possible. Local development of convective and dynamical instabilities may result in the radiation of secondary gravity waves (Dunkerton and Fritts, 1983); however, the most important result is the production of turbulence. Turbulence generation is initially confined to regions of dynamical or convective instability within the wave field. Following generation, turbulence may be advected away from the unstable zone, whereas the actively unstable region propagates with the wave.

The most important consequence of saturation on the dynamics of the large-scale circulation is the momentum deposition resulting from the amplitude-limiting mechanism (Lindzen, 1981). Secondary effects produced by the turbulent layers include heat as well as constituent transport. The study by Schoeberl et al. (1983) suggests that the turbulent heat transport drives the mean state towards an adiabatic lapse rate. Using a quasi-linear initial-value model, Walterscheid (1983) found large-amplitude gravity wave saturation to produce a rapid reduction in both the intrinsic phase velocity of the wave and the eddy diffusion needed to balance wave growth. There is also some heating due to wave and turbulence dissipation.

The above describes a very simplistic view of the saturation of an isolated monochromatic gravity wave. Not well understood is the detailed evolution of the wave field during saturation, including the production of turbulence and possible wave frequency broadening (Weinstock, 1976, 1982). Advances in this area will have immediate consequences for observational programs. For example, to what extent can waves be partially reflected from neutrally buoyant layers produced by turbulent zones or from large velocity shears due to differential momentum deposition? And could we expect to see evidence of such reflections in the data? Reflection at an internal shock and wave scattering due to localized dissipation were observed in the numerical experiments of Dunkerton and Fritts (1983). Finally, there is some evidence which suggests that multiple wave interaction can lead to saturation although this process has not been studied in detail.

The spatial and temporal variability of gravity waves entering the mesosphere is poorly understood at present. Clearly, the upward flux of waves at the stratopause is a function of the production of waves in the troposphere, their transmission, and zonal and meridional propagation (Dunkerton, 1982b; Schoeberl and Strobel, 1983). The obvious tropospheric gravity wave sources are unstable wind shear, topography, and convection. Others may be important as well. Wind shear produces waves with phase velocities characteristic of tropospheric wind speeds, while topography generates gravity waves with a phase velocity distribution centered about zero. Of the three dominant gravity wave sources, the phase velocity spectrum associated with convection is the least understood. However, it is reasonable to suppose that the phase speed distribution is broad and centered near tropospheric wind speeds. Characteristic scales and amplitudes, as well as the distribution and variability of the above sources, are not well known at present (Lindzen, 1983). Such information requires additional theoretical work and detailed tropospheric observations of gravity wave forcing and structure.

The transmission of gravity waves into the mesosphere their propagation in and interaction with a variable enviror effects include refraction, reflection, and critical-level a variations of Ū and N^2 with height. These variations caus vertical wavelength and group velocity of the wave and may l filtering of the gravity wave spectrum (Booker and Bretherton, Reddy, 1967). For motions with small intrinsic frequencies mean flows and radiative damping are also likely to be im 1982; Schoeberl et al., 1983). Spatial inhomogeneities sources or transmissivity are likely to produce a vertica broadening of the zonally averaged momentum deposition a excitation of large-scale gravity waves and planetary wave understand the consequences of gravity wave momentum depositio production in the middle atmosphere, however, the morphology gravity waves into and through the middle atmosphere must be b

4. OBSERVATIONS

A wide variety of techniques have been used to study g turbulence in the middle atmosphere. These are discussed t terms of not only their present capabilities and their relativ disadvantages but also in terms of future developments. T exhaustive, but represents the views of a limited number scientists concerning which combinations of systems are likely maximum amount of useful information on many of the import middle atmosphere dynamics. More comprehensive descriptions o can be found in MAP Handbooks, Volumes 12-15.

While a number of important wave and turbulence parameters have already been measured, there is a need for simultaneous measurements of those parameters that unambiguously define wave characteristics before there can be significant advances in our understanding of the middle atmosphere. In the following section, some specific recommendations are made as to how currently existing stations and future systems or groups of systems could best be deployed to improve our knowledge of the wave and turbulence fields.

a. Techniques

1. MST Radars

Powerful radars operating at VHF and UHF can be used to measure winds, waves, and turbulence parameters in the middle atmosphere by observing the intensity, Doppler shift, and spectral width of echoes obtained from refractive index irregularities. The radars have a temporal resolution as short as 1-2 minutes and a spatial resolution (along the radar beam) as short as 30-300 m. These radars have the unique capability of being able to measure vertical velocities with reasonable accuracy. Three radar beam directions are required to fully resolve the wind components. Winds in the troposphere and stratosphere (up to 30 km) can be measured continuously. In the mesosphere, wind measurements are possible in the 60-90 km region by day and (using echoes from ionized meteor trails) in the 80-105 km region by day and night, subject to sufficient electron density gradients. The "gap" region from roughly 35-55 km is difficult if not impossible to observe with existing MST radars without extensive temporal averaging.

A radar with sufficient sensitivity to obtain useful echoes from the mesosphere, stratosphere and troposphere (MST) can cost in excess of $1M but smaller radars which can study the lower stratosphere and troposphere (ST) cost an order of magnitude less. It has been demonstrated that these radars can operate continuously with minimum maintenance, which considerably reduces operating costs. The smaller systems can be made easily transportable so that networks of ST radars with variable spacing are possible.

2. Partial Reflection Radars

Partial reflection (PR) radars operating at frequencies near 2-3 MHz use the spaced antenna technique to measure the horizontal wind field in the 60-100 km height range by day and in the 80-100 km range by night. The meridional and zonal components are observed simultaneously in a common volume that typically has a radius of about 4-15 km and a depth determined by the pulse length, which is 2-4 km. PR radars are well suited for studies of gravity waves with periods greater than about 15 min because of the excellent height and time coverage and moderate-to-good spatial and temporal resolution. However, the observations are limited by the intermittency of the reflecting mechanisms which are usually turbulent in character above 80 km and quasi-specular in nature at lower levels. PR radars can operate for long periods with little attention. Small PR radars can be made transportable and with low cost ($\gtrsim$\$20K). To improve the system sensitivity it is possible to implement signal processing techniques such as coherent integration of the signal and pulse coding. These improvements could extend the observable altitudes down to perhaps 50 km at mid-day. By making the radars phase coherent, it may also be possible in the future to measure vertical velocities.

3. Meteor Radars

Meteor radars measure the line-of-sight Doppler velocities of meteor trails drifting under the influence of the wind. The trails occur randomly in space and time and are usually observed in the 80-105 km height region with a large diurnal variation of echo rates. Significant averaging in space and time is usually required to obtain the winds, so that meteor radars are best suited to measuring the prevailing and tidal components. However, some meteor radars with good (~2 km) height resolution can be used to measure gravity wave amplitudes and vertical wavelengths. Multi-station techniques can be used to investigate turbulence and small-scale wind structure in the lower thermosphere. MST radars can also be used to obtain meteor winds.

4. Lidars

Lidars use Rayleigh scattering from atmospheric molecules to measure neutral density and temperature. The height covered is 30-90 km at night and 30-60 km during the day. The height and time resolution depend on the amount of temporal averaging used, and values in the range 100 m-1 km and 15 min-1 hr are currently achieved. The errors in temperature at night typically range between 0.1 K at 30 km and 10 K at 80 km for data averaged over 2 hours with a height resolution of 2 km. Lidar systems can operate continuously subject to meteorological conditions, and can be made easily transportable. In the near future it should be possible to achieve a ten-fold gain in accuracy by increasing the laser mean power and the collecting area of the receiving telescope. It may also be possible to measure winds in the lower stratosphere by, for example, utilizing the Doppler shift of scattering from aerosols. The current cost of a lidar station is about $200-300K.

5. Rocket Techniques

The Meteorological Rocket Network (MRN) provides data on the zonal and meridional wind components and temperature in the height range 20-70 km with a vertical resolution of a few hundred meters. Although the time resolution of rocket observations is poor (two soundings per week on average at each station), gravity waves can be studied by removing the mean background state from individual profiles. Valuable information is provided in the gap region not presently covered by MST radars. Observations have been made for more than 15 years at stations covering a wide range of latitudes, longitudes, and seasons.

Recently, a variety of high-resolution rocket-borne measurement systems have been employed for detailed studies of middle atmosphere structure and composition. Those of relevance to the study of gravity wave and turbulence processes include high-frequency accelerometers, electron density probes and trace constituent sensors, among others.

Future prospects in this field appear to be primarily in those ongoing high-technology rocket programs designed to study specific aspects of the gravity wave and turbulence fields. Nevertheless, the MRN data analysis of gravity waves will remain important as a counterpart to MST radar measurements and a complement to lidar measurements in the future.

6. Balloon Techniques

Radiosondes provide a large set of data on the temperature and wind fields in the range 0-30 km. The accuracy of the measurements is sufficient for meteorological purposes (1 K in temperature and 5 ms^{-1} in wind speed) but they typically do not provide a detailed description of the wind structure. However, large balloons carrying two vertically separated anemometers have provided temperature and wind measurements in the stratosphere with excellent height resolution (1 m) and accuracy (0.05 K and 0.1 ms^{-1}) and have been used to study gravity waves and turbulence.

7. Aircraft Techniques

In the lower stratosphere (up to 21 km) research aircraft equipped with inertial platforms, air motion sensors, and temperature and trace species sensors can be utilized to provide information on wave and turbulence structure with a high degree of accuracy at the smaller horizontal scales.

Such measurements could provide data complementary to the remote sensing methods.

8. Other Techniques

Photographic studies of airglow emissions such as from OH and Na and of noctilucent clouds can provide very useful information on the horizontal structure and phase velocities of waves near the mesopause. High vertical resolution (~100 m) investigations of the sodium layer by lidars can provide information on the periods and vertical wavelengths of waves in the 80-100 km region.

b. Topics

1. Turbulence

Radar methods provide a powerful tool for studying turbulence in the middle atmosphere (for details, see Balsley and Gage, 1980; Röttger, 1980). The backscattered echo power and the Doppler spectral width of the signal returns are directly related to turbulence intensity. The echo power is a direct measure of one spatial Fourier component of the refractive index variation produced by a turbulent region, while the spectral width (used with caution) is a measure of the variance of turbulence velocities.

Turbulence spatial characteristics have already been studied at a number of sites via the backscatter power structure. The presence of vertically thin, horizontally extended turbulent regions that exist for many hours has been noted in both the stratosphere and lower mesosphere (Czechowsky et al., 1979; Sato and Woodman, 1982). While some exceptions to this general picture exist (i.e. in the high-latitude summer mesosphere), they can probably be considered typical.

Estimates of vertical diffusion can be made using statistical properties of the thin turbulent regions (Woodman et al., 1981). This is of particular importance in the current context since enhanced diffusivity increases gravity wave damping and the corresponding mean flow accelerations. Estimates of stratospheric diffusion and turbulence dissipation have been obtained from the observed dispersion of rocket vapor trails (Rosenberg and Dewan, 1975) and high-resolution balloon data (Cadet, 1977) among others. Current radar estimates of vertical diffusivity in the lower stratosphere suggest values that may be appreciably larger than those obtained by aircraft techniques (Lilly et al., 1974). Further measurements appear necessary to address this disparity.

The possibility of using radar systems with very good vertical resolution (tens of meters) to study the space-time structure of turbulence within the layers is exciting, and should allow us to better understand the underlying generation mechanisms (i.e. dynamical and convective breaking of the waves). In this regard,. the use of special rocket and balloon-borne techniques (Philbrick et al., 1983; Barat, 1983) concurrent with radar observations to obtain high-resolution structure of turbulent regions would appear important for understanding the generation mechanisms of turbulence and would enable a valuable intercomparison between techniques.

The use of Doppler spectral width to measure turbulence intensity has yet to be fully exploited (Sato and Woodman, 1982; Hocking, 1983). Since the velocity variance is directly related to the eddy dissipation rate, it is clear that a greatly increased observational program using spectral width estimates of eddy dissipation rates would have direct relevance to the development of more accurate general circulation and mechanistic models. Energy dissipation rates can also be used to infer vertical diffusivity and heating, thus spectral width measurements may provide an alternative method of determining vertical diffusivity. Specral width measurements, however, require a narrow radar beam and a correspondingly large antenna area.

Finally, the general characteristics of the turbulence structure profiles can be expressed in terms of the refractive index structure constant C_n^2 (Tatarskii, 1971). This parameter is useful, for example, in comparing radar, optical, and other turbulence measurements.

2. Gravity Waves

A significant amount of information on middle atmosphere gravity waves has already been obtained by existing techniques. Radars can provide a detailed description of the wind field as a function of height and time. They can also produce spectral descriptions of the wind field fluctuations as a function of frequency (Balsley and Carter, 1982). Lidars provide similar information for the temperature fluctuations (Chanin and Hauchecorne, 1981). Data from rocket networks can reveal long term statistics on the geographical and seasonal variation of the wave field (Hirota, 1983). Rocket data also provide instantaneous profiles of temperature and wind (Theon et al., 1967) from which gravity wave processes can be inferred.

Two important parameters about which relatively little information has been collected are the horizontal wavelengths (λ_h) and phase velocities (c) of gravity waves. Some information on these parameters has been obtained from studies of airglow emissions and noctilucent clouds (Armstrong, 1982; Hersé et al., 1980; Haurwitz and Fogle, 1969). Initial radar estimates of λ_h and c were made by Vincent and Reid (1983) and Fritts et al. (1983). Vincent and Reid (1983) also made the first direct measurements of another important quantity, the upward flux of horizontal momentum ($\overline{u'w'}$) in the mesosphere, and Vincent (1983) used rotary spectra to obtain a lower limit on the fraction of upward propagating, low-frequency gravity waves in the mesosphere and lower thermosphere. The latter study suggests an upward flux of energy and momentum consistent with the requirement of gravity wave drag.

Two interpretations have been advanced to account for the low-frequency ($\omega < N$) and low (horizontal) wavenumber spectra observed in the middle atmosphere. One is that the motions are due to a spectrum of internal gravity waves analogous to the "universal" wave spectrum applied to the ocean (VanZandt, 1982). Such a theory is consistent with both the apparent role of gravity wave transport, drag, and diffusion in middle atmosphere dynamics and the observed spectral character of atmospheric fluctuations. A second interpretation, based upon the theory of two-dimensional turbulence, also appears to be consistent with certain spectral observations (Gage, 1979; Lilly, 1983), but this theory requires the presence of propagating gravity waves as the primary coupling between the lower and middle atmosphere and is concerned primarily with the spectral distribution of kinetic energy. The actual state of the atmosphere, of course, may involve a combination of gravity waves, two-dimensional turbulence, and other motions, with further studies needed to delineate their relative importance.

Gravity wave observations to date have provided good preliminary information on motions, processes, and spectra using a variety of techniques. Often, however, such observations are made without knowledge of the mean velocity and static stability profiles. This is a major shortcoming (particularly the lack of $\bar{u}$) because it causes ambiguities in the determination of the characteristics and/or consequences of the wave motions that might otherwise be inferred.

5. FUTURE RESEARCH NEEDS

a. Modeling Needs

Because they tend to be computationally efficient and allow individual processes to be studied in isolation, mechanistic models will probably continue to play a major role in the development and testing of parameterizations for gravity wave-mean flow interactions. Both the quasi-geostrophic models and the global primitive equation models will be useful tools. We anticipate, however, that there may be less emphasis on zonally symmetric models in the future, particularly for the study of wave-mean flow interactions in the winter hemisphere. The current primitive state of knowledge of gravity wave morphology and of the detailed physics of wave breaking allows for a wide range of assumptions in present models. Ideally, mechanistic models that properly handle wave-mean flow interactions will provide some useful constraints on the possible characteristics of the observed wave climatology. However, there is little prospect that modeling can be in any sense a substitute for observations.

It should be cautioned that measured gravity wave fluxes and other parameters will not be able to be used directly in middle atmosphere models. One reason for this is that measured quantities depend on atmospheric conditions in the troposphere, stratosphere, and mesosphere that may be very different from those existing in a model. However, measurements of the global gravity wave morphology should allow the development of schemes that can consistently represent the proper dependence of the large-scale flow on gravity wave processes.

b. Theoretical Needs

Theoretical studies are needed to address a number of problems that are unlikely to be solved using existing observational techniques. The most obvious of these relate to the saturation process itself. In particular, studies are needed that address the detailed mechanisms and consequences of saturation, including wave scattering and reflection, multiple wave saturation, and the effects of temporal and spatial variability of saturation. The former studies are necessary to understand the evolution of a saturating gravity wave spectrum; the latter is needed to correctly incorporate the effects of saturation and its variability in mechanistic and general circulation models of the middle atmosphere.

Other areas in which theoretical work is needed are the identification and quantification of the dominant tropospheric sources of gravity waves and studies of wave propagation and filtering through wave-wave and wave-mean flow interactions. Theoretical studies of gravity wave sources in conjunction with high-resolution observations may help determine the phase speed and horizontal wavelength distributions as well as their geographical and temporal variability. These distributions are poorly known at present, but they are expected to have a major impact on the occurrence and the effects of saturation in the middle atmosphere. Likewise, the propagation of gravity waves through and their interaction with a variable environment will influence the character and occurrence of saturation. It is also important to determine to what extent the concept of a universal gravity wave spectrum can be applied to the atmosphere.

c. Observational Needs

1. Gravity Wave and Turbulence Climatology

There is a clear need to extend our studies of the climatology of atmospheric gravity waves and turbulence. Observations of the geographical and temporal distributions of gravity wave sources, energies, and momentum and heat fluxes as well as turbulent diffusion are required. The distributions of momentum fluxes ($\overline{u'w'}$ and $\overline{v'w'}$) and heat fluxes ($\overline{v'T'}$ and $\overline{w'T'}$), in particular, have direct implications for modeling the large-scale circulation and will depend on the dominant sources and the propagation of gravity waves into the middle atmosphere. Measurements of turbulent diffusion and spectral width are needed to address the rate of gravity wave energy dissipation and the effects of diffusion in the middle atmosphere.

It is also important to address the vertical transport of energy and momentum by the full spectrum of gravity waves under various conditions. To this end, studies of low-frequency motions using rotary spectra and filtering through radiative cooling, wave-wave, and wave-mean flow interactions appear relevant.

Momentum flux, energy, turbulence intensity, and rotary spectrum measurements are currently possible with multiple-beam radar systems; heat fluxes could be determined with combinations of radars and lidars.

2. Case Studies

Case studies of nearly monochromatic wave motions providing the mean and perturbation wind fields and the distributions of vertical wavenumber would permit comparisons with theoretical models and provide evidence of important processes and interactions. Independent measurements of the associated temperature fields would permit a check on the wave parameters inferred from radar measurements. Observations of wave excitation and dissipation (or saturation) are particularly important in this regard. It would also be useful to identify the frequency of occurrence of the various gravity wave processes and interactions thought to be important in the middle atmosphere.

One example of a useful case study is nearly monochromatic gravity wave saturation. Saturation is associated with either $|\frac{\partial T}{\partial z}| \sim \Gamma$ or $|u'| \sim |c-\bar{u}|$. Because there are uncertainties in estimating c using data from a single station, however, saturation may be identified most unambiguously in measurements of the temperature structure. Because c is constant and $\bar{u}$ may change with height, $|u'|$ need not remain constant above the saturation level.

3. Measurement of λ_h and c

Two gravity wave parameters of particular significance are the horizontal wavelength (λ_h) and the (horizontal) phase velocity (c). They are important because they are essentially constant following the wave motion and they determine the occurrence and distribution of gravity waves in the middle atmosphere. Other relevant wave parameters like the intrinsic frequency ($k(c-\bar{u})$) and the vertical wavenumber ($m = \frac{2\pi}{\lambda_z}$) are not constant, but depend on N^2 and $\bar{u}$. Determination of the phase speed distribution of gravity waves near their source regions in the troposphere and in the middle atmosphere would permit a quantitative assessment of the effects of filtering and wave-wave interactions as the gravity waves propagate vertically. Horizontal wavelength measurements would help establish the degree of homogeneity in the mesospheric response to gravity wave saturation.

Estimates of λ_h and c can be obtained in certain instances with present radar and lidar systems using multiple-beam techniques. However, such estimates are subject to potentially large errors and may be biased towards relatively small-scale waves ($\lambda_h \lesssim 200$ km) because of small horizontal beam separations. It would be desireable, therefore, to make more direct radar and lidar measurements at a range of spacings from a few tens of km upwards in order to measure those wavelengths and phase velocities most relevant to middle atmosphere dynamics. Such spacings are considerably less than that required to address the geographical distribution of gravity wave saturation and turbulent diffusion.

4. Measurement of Mean Winds

In addition to gravity wave and turbulence measurements, long term measurements of the mean zonal and meridional wind components in the mesosphere and lower thermosphere are required. At present, the climatology of the mean zonal wind at these levels is not well known, especially in the tropics. The current data base for the mean meridional wind is completely inadequate. The latter is particularly important since gravity wave drag in the mesosphere is primarily balanced by the Coriolis torque due to the mean meridional motion.

d. Observational Networks

As discussed in several of the above sections, it would be desireable to establish networks of radar and/or lidar systems for the following reasons:

i) The horizontal wavelengths and phase velocities of monochromatic atmospheric gravity waves can be measured more reliably by making observations from at least three spatially separated points. Because the wavelengths of longer waves cannot be accurately determined using small spacings, it will be necessary to use a range of spacings.

ii) Studies of the global morphology of gravity waves require that several such facilities be established at geographically distinct locations. Such systems should make extended observations to determine seasonal and inter-annual variability. The potentially important effects of orography can be examined by establishing sites near extensive mountain ranges and by comparing these results with observations taken in orographically smooth regions.

Other combinations of observing systems would also provide important information on gravity wave propagation and dissipation processes and morphology. Co-located lidar and radar facilities, for example, would permit much more detailed observations of gravity wave saturation in the mesosphere. Saturated wave amplitudes could then be compared directly with perturbation lapse rates for both narrow- and broad-spectrum saturation. Meteorological rockets would provide an important complement to both radar

(MST or PR) and lidar facilities through the addition
temperature, and gravity wave structure in regions where no
wind data is available. Such data would make possible studies
propagation and the onset of saturation.

One final recommendation pertains to establishing such
the tropics. Extended tropical observations, particularl
degrees of the equator, will yield (in addition to the low-
waves) important new information on long-period equatorial wav
exist only in the tropics and comprise the major mechani
transport into the middle atmosphere in that region.

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GLOSSARY

c	horizontal phase velocity
k	horizontal wavenumber $(= \frac{2\pi}{\lambda_h})$
m	vertical wavenumber $(= \frac{2\pi}{\lambda_z})$
N	Brunt-Vaisala frequency
T	temperature
$\bar{u}$	mean horizontal motion
u'	horizontal perturbation velocity
z	height coordinate
Γ	adiabatic lapse rate $(= \frac{g}{C_p})$
λ_h	horizontal wavelength
λ_z	vertical wavelength
ω	intrinsic wave frequency $(= k(c-\bar{u}))$

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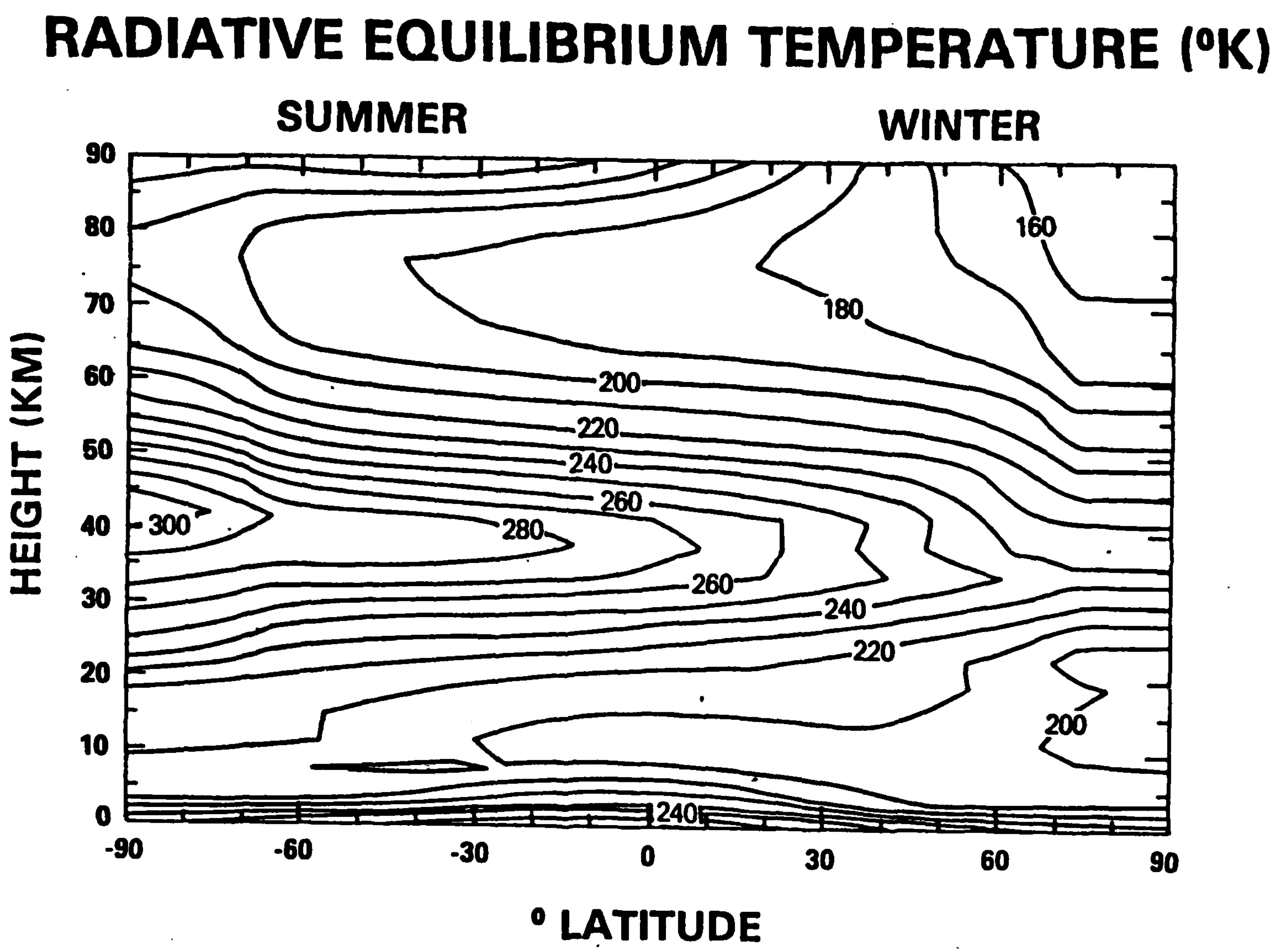

Figure 1. Calculated radiative equilibrium temperatures as described in the text. Units are K.

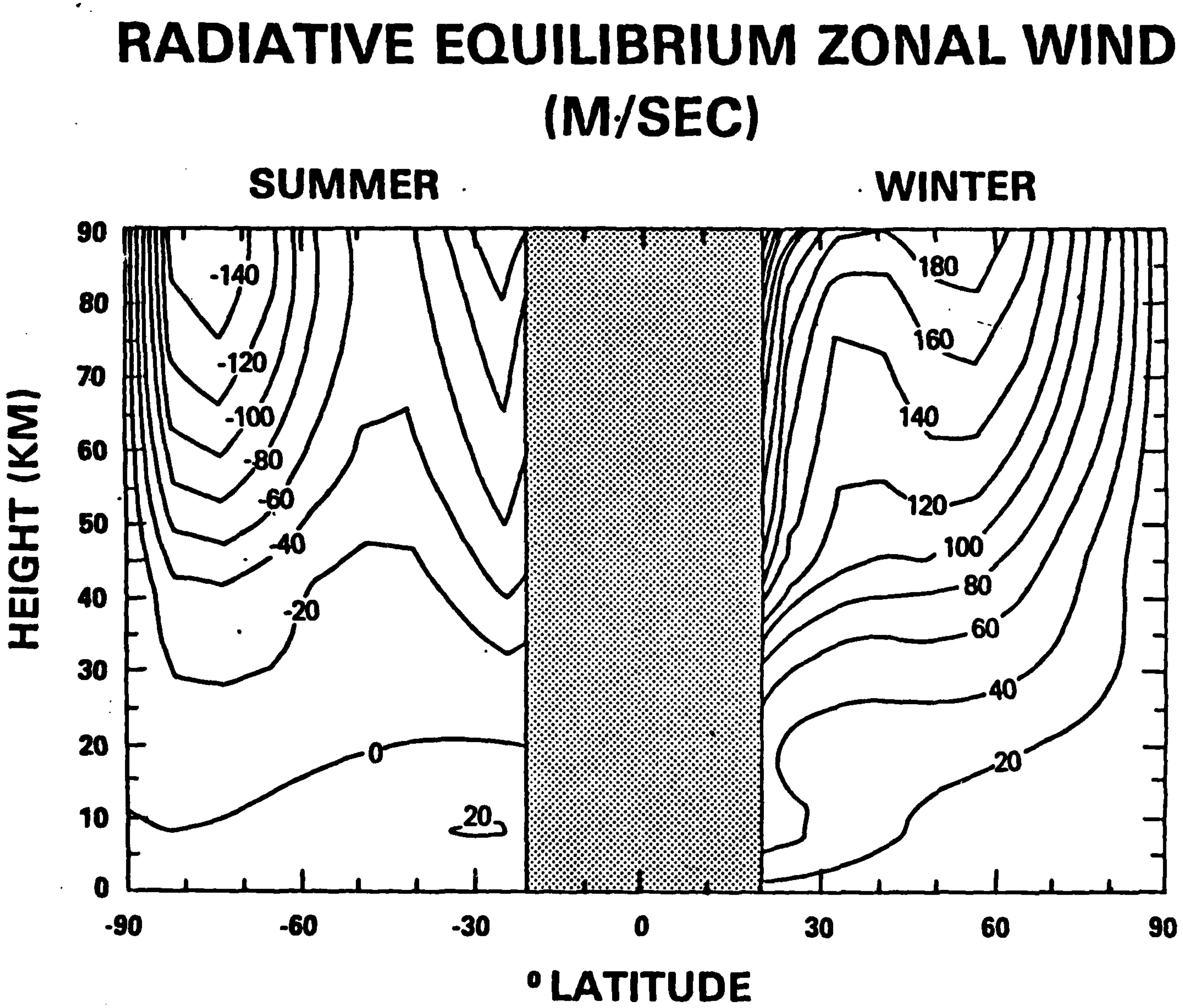

Figure 2. Geostrophic mean zonal winds calculated from the radiative equilibrium temperatures shown in Fig. 1. No values are shown near the equator because of the inapplicability of the geostrophic formula there. Units are m/s, and westerly winds are positive while easterly winds are negative.

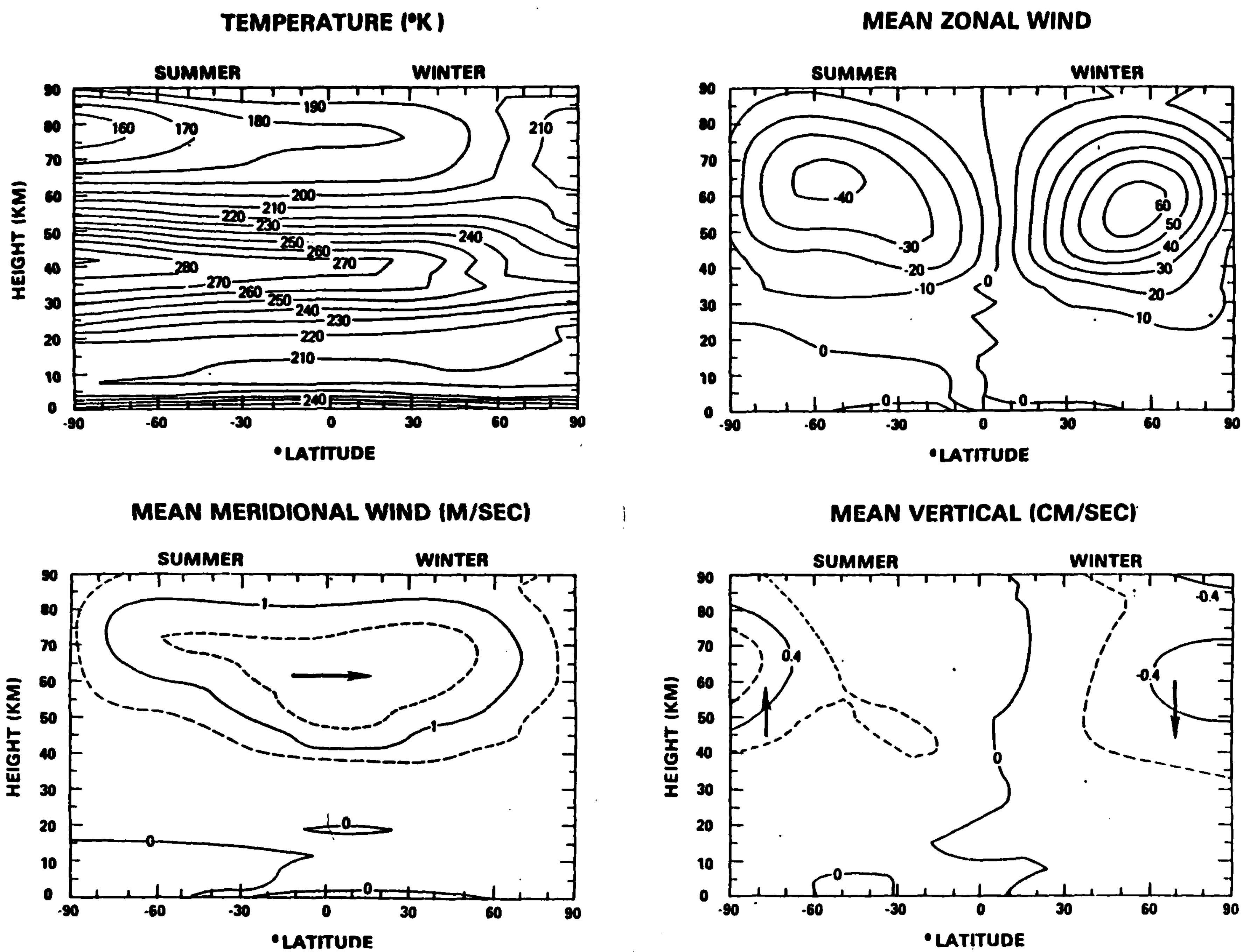

Figure 3. Model calculated zonally-averaged temperature field in K (left-top); mean zonal wind in ms^{-1} (right-top); mean meridional wind in ms^{-1} (left-bottom);

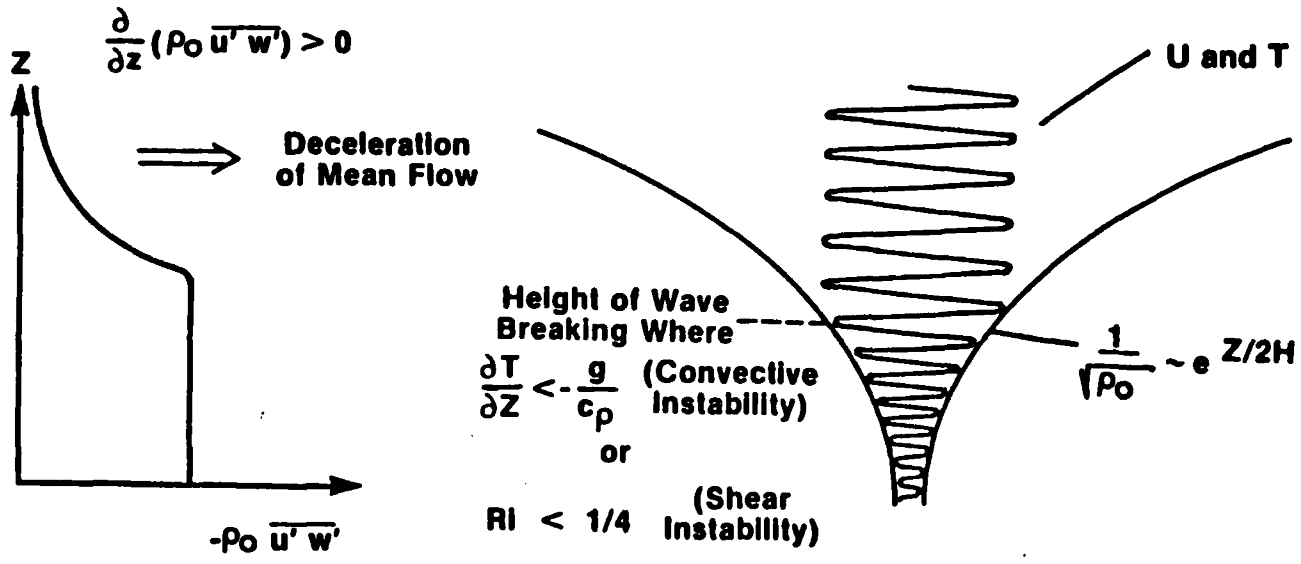

Figure 4. Schematic of gravity wave breaking and the resulting vertical flux of zonal momentum.

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